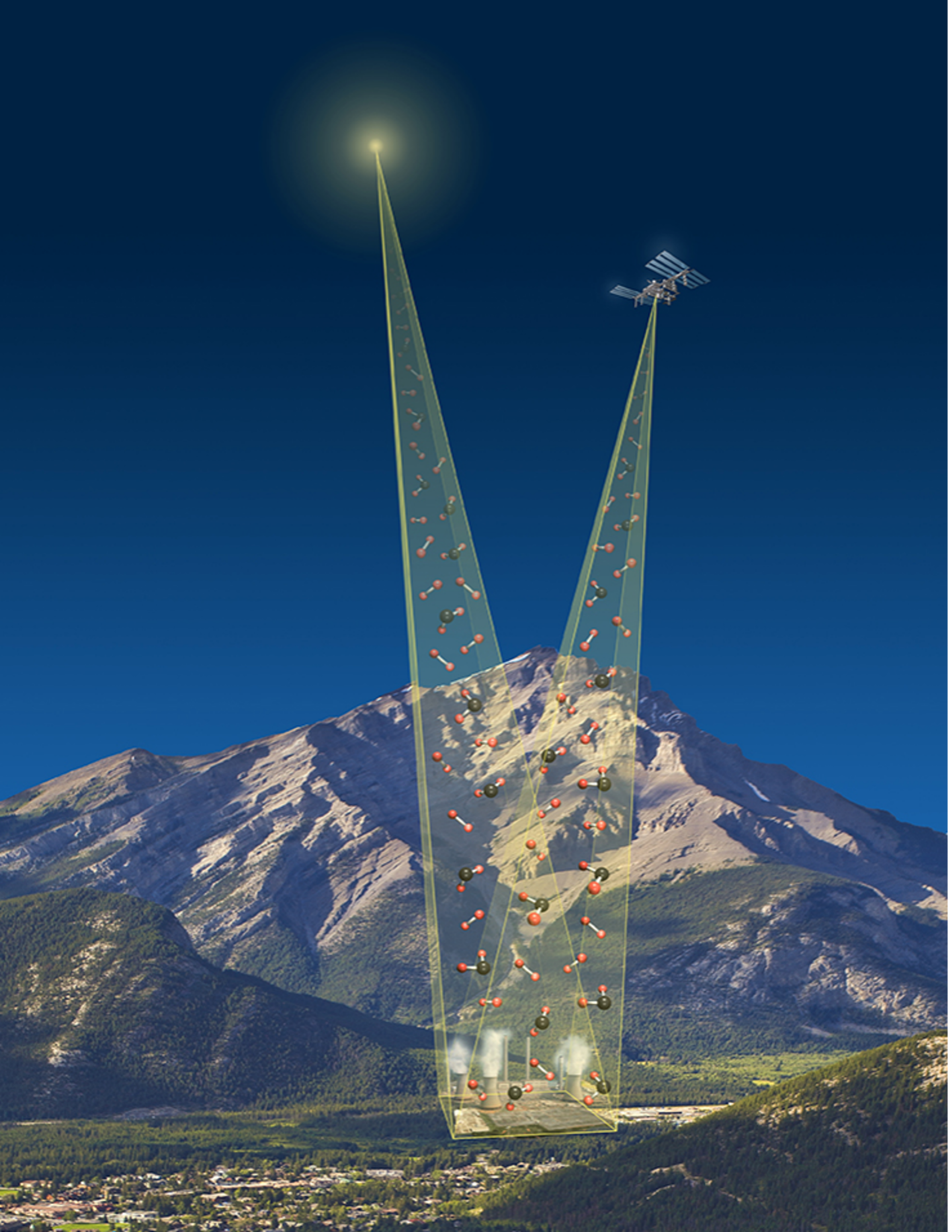

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Automated Scheduling for the Orbiting Carbon Observatory 3 Mission

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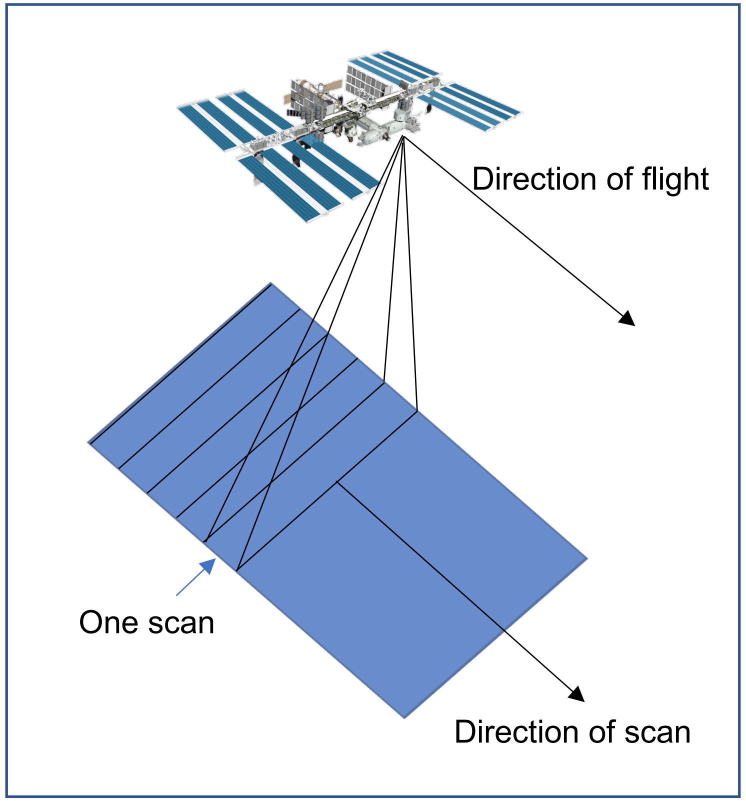
Overview

- CLASP Scheduling System
- OCO-3 Mission
- Scheduling Operational Modes
- Checking Visibility
- PMA Calibration Scheduling

CLASP

- **C**ompressed **L**arge-scale **A**ctivity **S**cheduler and **P**lanner (Knight and Chien 2006)
  - Scheduler for space-based instruments that can be modelled as pushbrooms
- Used by OCO-3 for scheduling science operations and instrument calibration



Pushbroom Imager

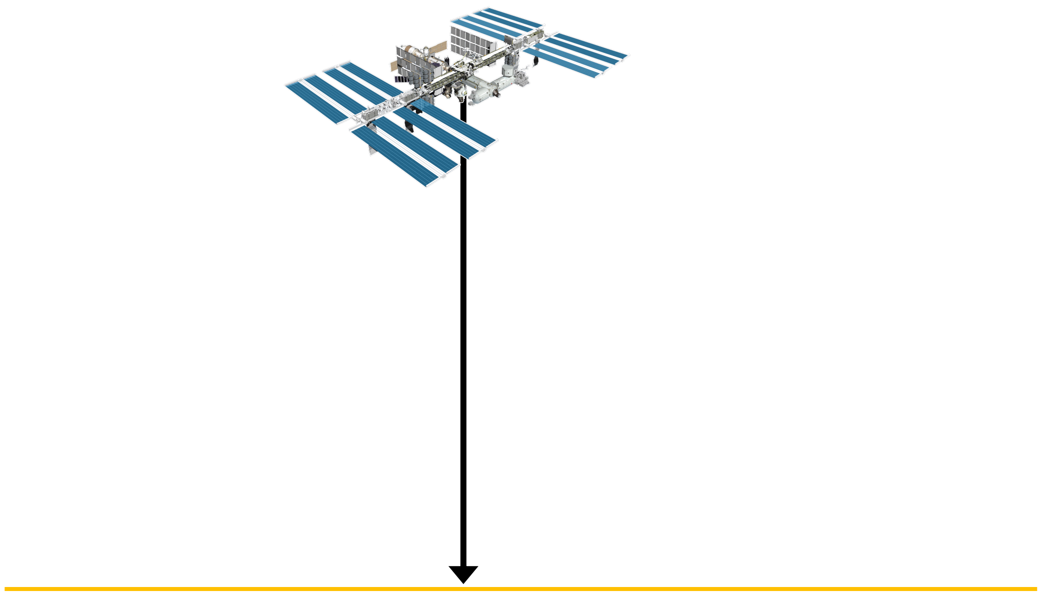
OCO-3

- Measures atmospheric CO_2 indirectly by measuring the intensity of solar radiation reflected off of CO_2 molecules in an air column
- Made from instrument built as a backup for OCO-2
  - Is able to do what OCO-2 can do (nadir, glint) and more due to PMA
- Launched to the ISS in May 2019
  - Installed on the Japanese Experiment Module – Exposed Facility
- Expected to begin nominal science operations in August 2019

SpaceX CRS-17 launch on May 4, 2019

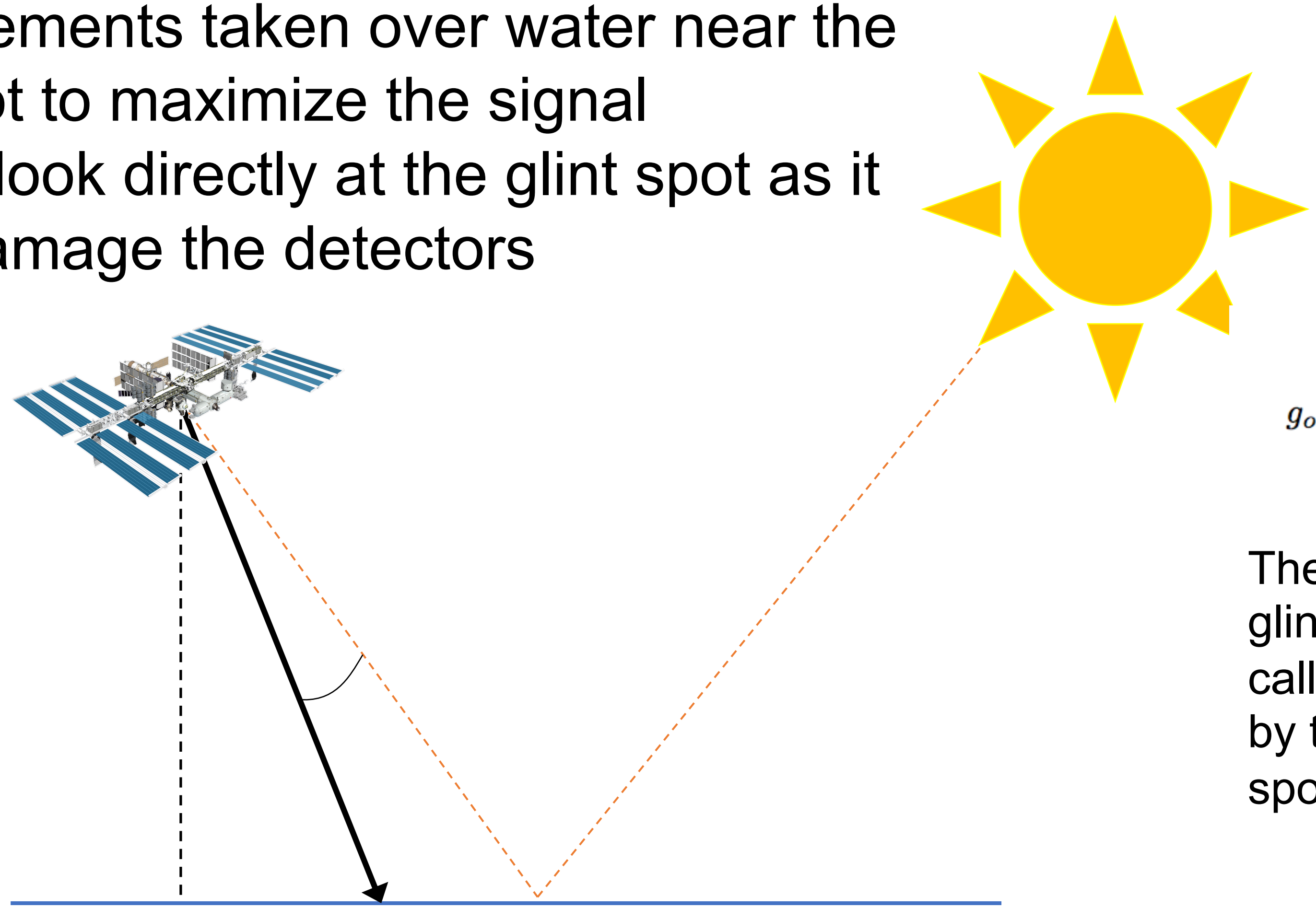
Operational Modes – Nadir

Default mode over land in the daytime



Operational Modes – Glint

Measurements taken over water near the glint spot to maximize the signal
Cannot look directly at the glint spot as it could damage the detectors

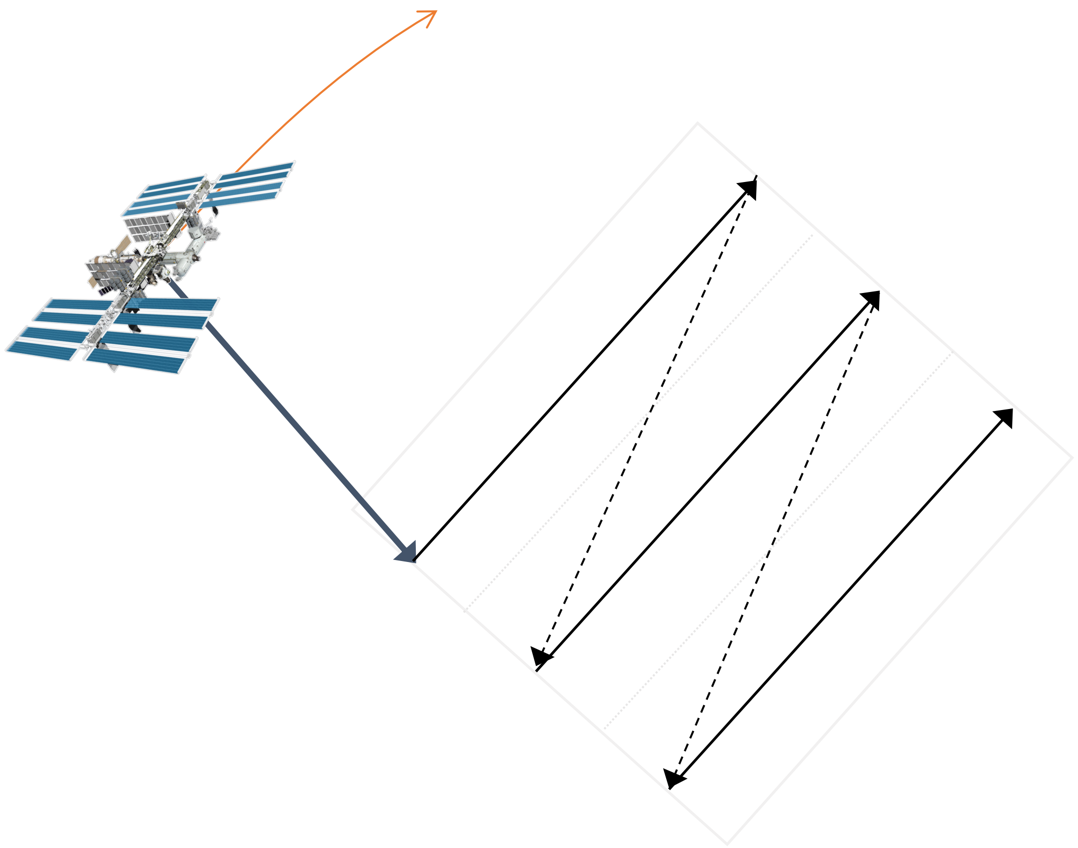


$$g_o = \begin{cases} offset_1 & 0 \leq g_{sza} \leq sza_1 \\ offset_2 & sza_1 < g_{sza} \leq sza_2 \\ \ldots & \\ offset_n & sza_{n-1} < g_{sza} \leq sza_n \end{cases}$$

The angular distance away from the glint spot the instrument looks, called the glint offset, is determined by the solar zenith angle at the glint spot

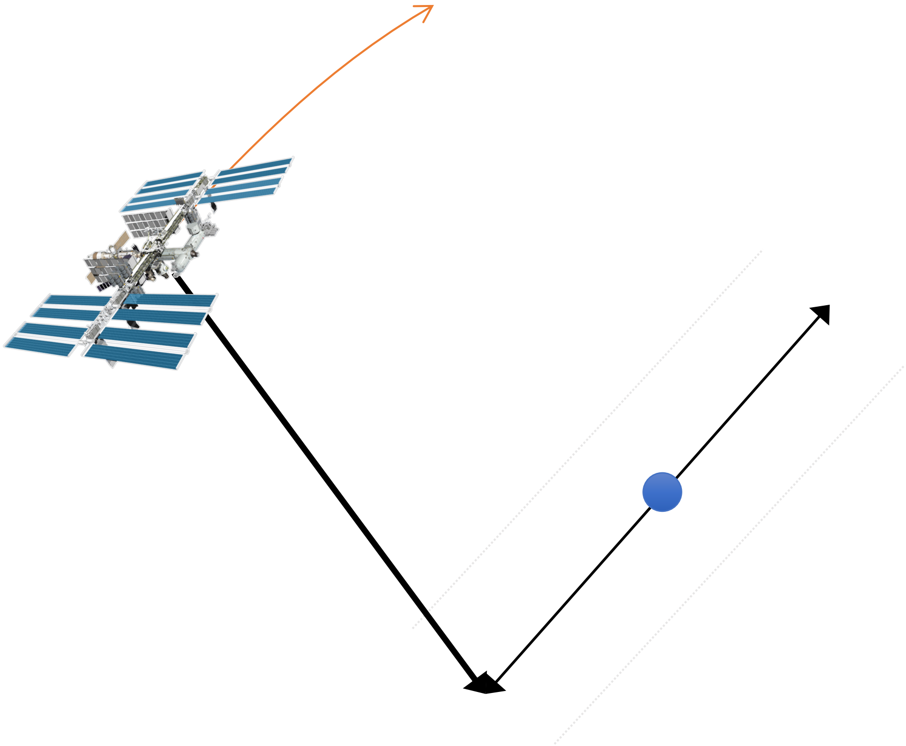
Operational Modes – Snapshot Area Map

Measurements taken over 80 km x 80 km regions of interest, such as a city



Operational Modes – Target

Measurements taken over a specific point, such as a validation site



Scheduling Observations

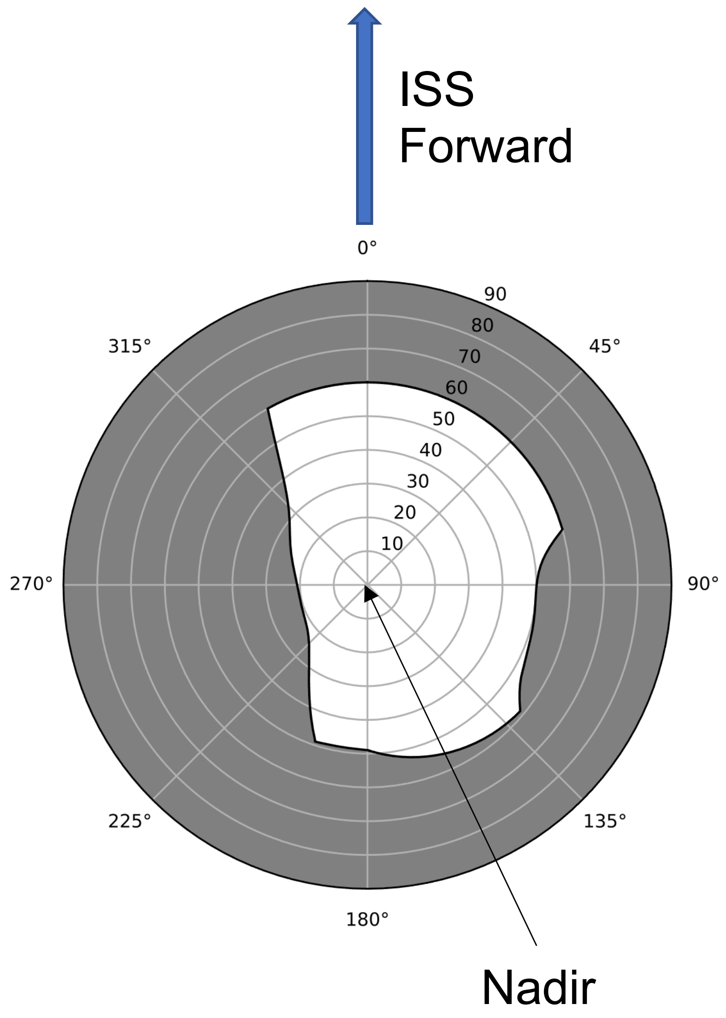
- Modes are scheduled mostly in priority order based on science value
    1. Snapshot Area Map
    2. Target
    3. Nadir – Glint (exclusive regions of visibility)
- Desire to schedule two Target Mode targets per day (for calibration/validation purposes) which slightly changes priority-based scheduling

Scheduling Observations

- Two-pass algorithm for scheduling
  - First pass: Identify all potential Snapshot Area Map observations and schedule up to two Target Mode observations only if they do not interfere
  - Second pass: Continue trying to schedule Target Mode observations even if they interfere with Snapshot Area Map observations until two Target Mode observations are scheduled
    - Schedule Snapshot Area Map observations
    - Schedule Nadir-Glint observations

Determining Visibility

- From OCO-3's position on the ISS, spacecraft features (like solar panels) occlude regions of its view
- Need to determine whether targets are visible when scheduling observations
    - FSW prevents bad pointings in real time, but want to prevent them from ever being scheduled
    - Snapshot Area Map targets are most complex because they are rectangular and defined by four corner points
- Occlusion mask is defined as a set of polynomials for longitudinal segments in the instrument frame of reference
    - Checking if a point is contained within the mask is constant time



Determining Visibility

- The fine movements of the PMA (pointing mirror assembly) are not modeled at schedule time
  - Do not know exactly where the PMA will be pointed at any given time
  - As a result, targets may be determined to be
    - Certainly visible
      - All parts of target are visible throughout entirety of observation
    - Certainly not visible
      - Parts of a target are not visible throughout entirety of observation
    - Possibly Visible
      - All parts of a target are visible at some point during observation, or cannot say for sure whether certainly visible or not visible
  - Only targets that are determined to be certainly visible can be scheduled

Determining Visibility – Problem

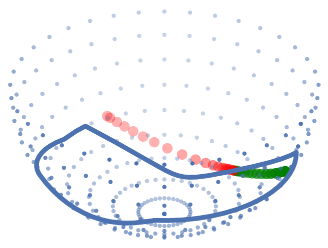
- Given inputs:
  - Target: a set of points on the Earth’s surface
  - Time range: start and end times of the desired observation window
  - Visibility set (V): A set of azimuth/elevation points in the satellite-centered reference frame that describe the instrument’s visibility
- Determine whether the target is visible to the instrument for the entire time range.

Determining Visibility – Checking Visibility at a Point in Time

- The target on the Earth's surface is translated into the spacecraft's reference frame in one of three ways:
  - Centroid: Project only the centroid of the target and check that the single point is in V.
  - Corners: Project the corners of the target and check that all are in V.
  - Configuration space: Define a configuration space that characterizes all points on the unit sphere that represent the centroid of a visible target. Project only the centroid of the target on the unit sphere and check that the point falls within the configuration space.

Determining Visibility – Centroid Method

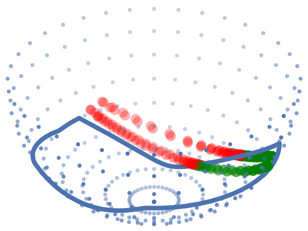
- Can never say that a target is certainly visible
  - At any time, even if the centroid is visible, it may be the case that one of the corners is not visible



Tracing the visibility of a target's centroid over time

Determining Visibility – Corners Method

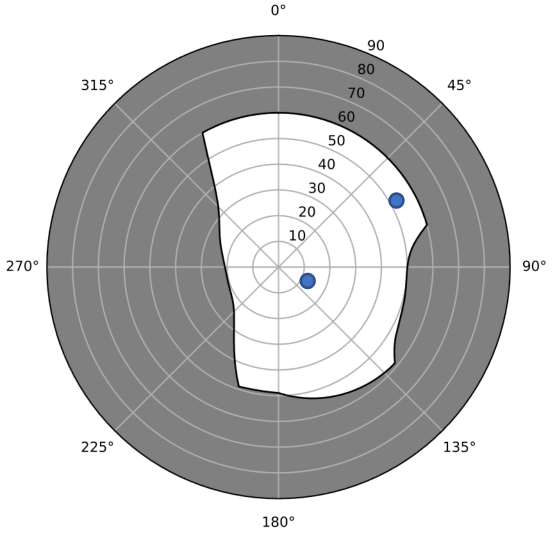
- If all corners are visible for the entire time range, we say the target is certainly visible
  - Not true with all mask shapes but specific to the one for OCO-3



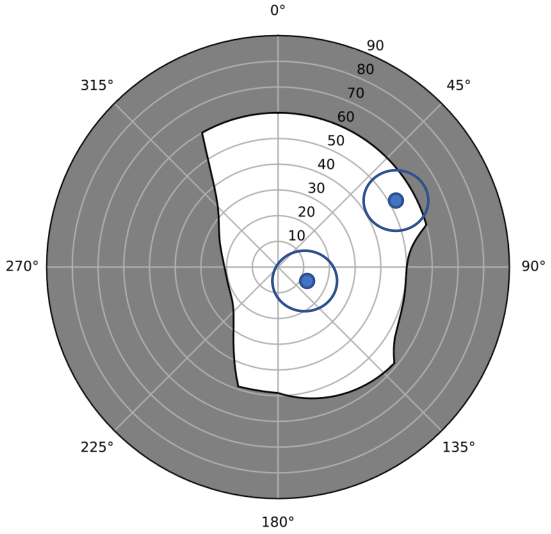
Tracing the visibility of a target’s corners over time

Determining Visibility – Configuration Space Method

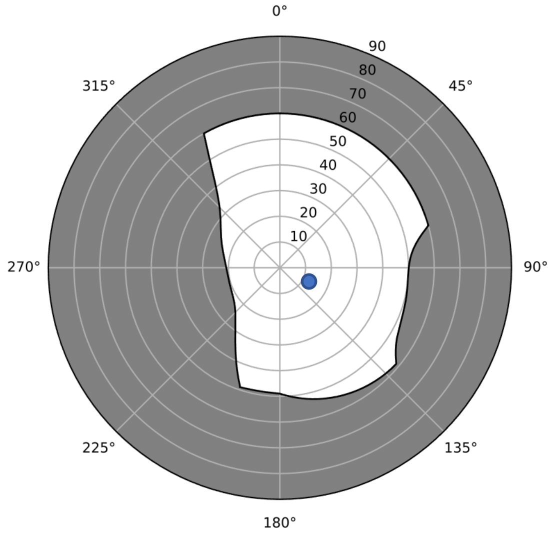
- A configuration space is created that contains centroids of targets that are certainly visible
  - The space is conservative and does not contain all possible visible centroids



Project a point onto the unit sphere



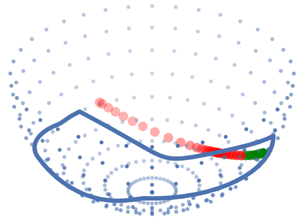
Create a circle around the point that would encompass all points within a target that has that point as its centroid



Points that do not intersect boundary configuration space

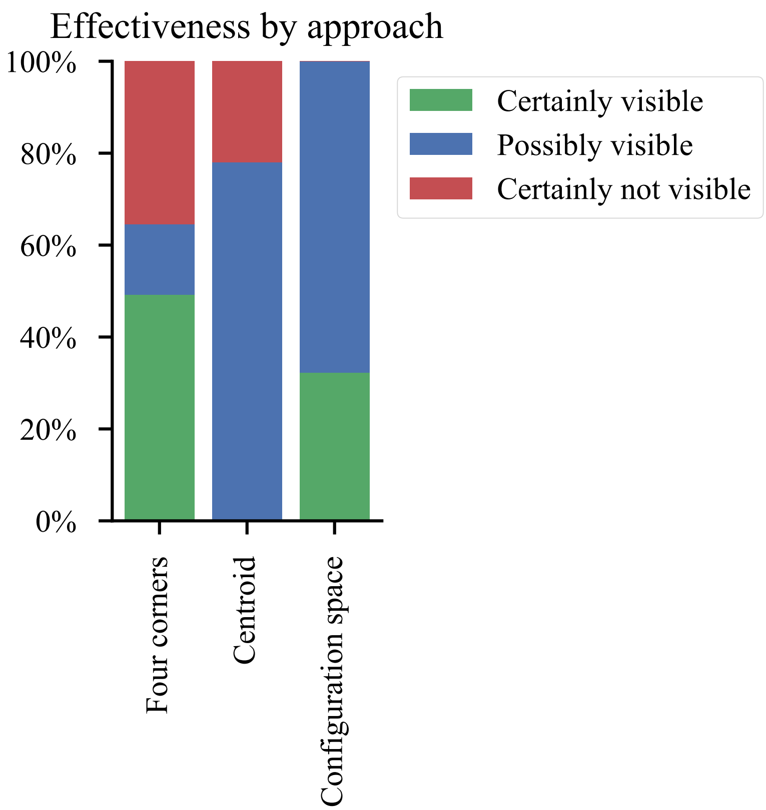
Determining Visibility – Configuration Space Method

- A configuration space is created that contains centroids of targets that are certainly visible
  - The space is conservative and does not contain all possible visible centroids



Tracing the visibility of a target’s centroid within the configuration space over time

Determining Visibility – Projection Method Results



The Corners method gives the highest amount of "certainly visible" results

Determining Visibility – Sampling Over Time

- To determine whether a target is visible over a range of time, we sample various points in time over that range. Increasing the number of samples may increase the confidence in our answer, but it will also increase the runtime of the algorithm

Determining Visibility – Sampling Over Time

- Constant step: Take evenly spaced samples, so that after every sample a constant amount of time passes before taking the next.
- Adaptive step: Take larger steps when the target is near the middle of the visibility set and smaller steps when it's close to the boundary.
- Max step: Take as large a step as possible, so that only the start and end times of the observation are considered.

Determining Visibility – Constant/Max Step

- Constant Step:
  - If the desired precision of the visibility window is one second, then the constant step size must be set to one second
- Max Step:
  - Requires the least computation, but it also gives us the least information about the target
  - If the target is not visible at either time, it’s almost certainly not visible for the entire duration of the observation
  - If it is visible at both times, the target is possibly visible

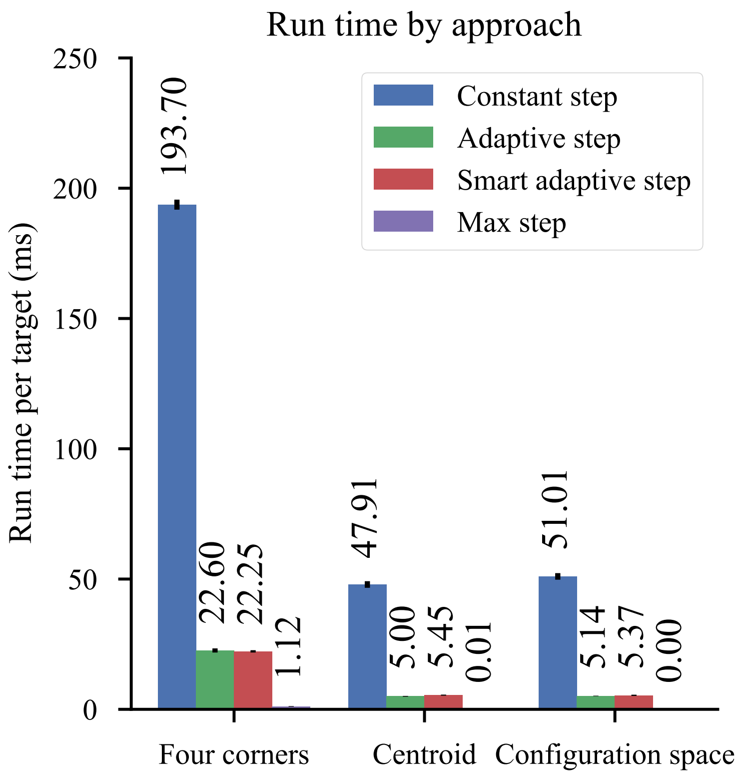
Determining Visibility – Adaptive Step

- Compute the angular distance between a point and the nearest point on the boundary of V
- Estimate the maximum angular velocity of any point
- Divide the distance by the velocity to obtain a lower bound on time it will take to reach the boundary to determine next step size
- Shortcoming is that velocity of a point varies with its location and this assumes a constant velocity

Determining Visibility – Smart Adaptive Step

- Project the nearest point on the boundary of V to the Earth's surface and compute the distance
- Can estimate maximum velocity of nadir point
- Divide the distance by the velocity to determine next step size

Determining Visibility – Runtime

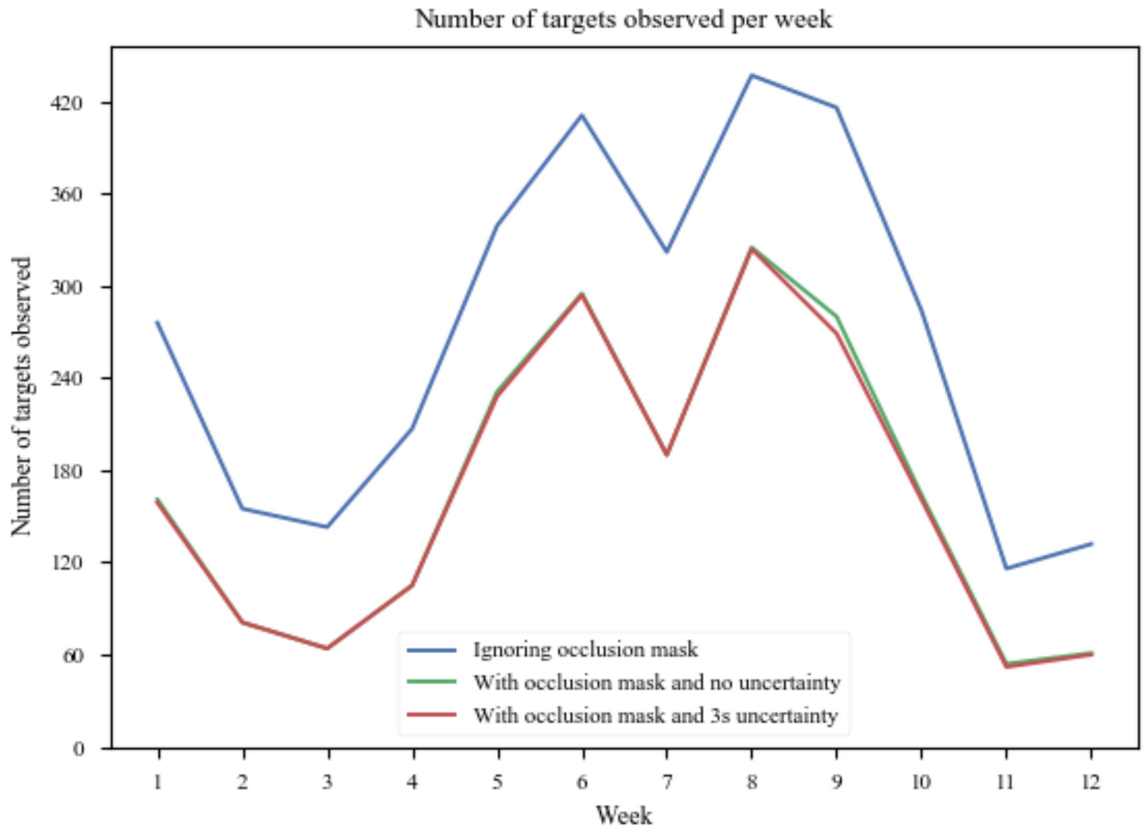


There is not a considerable difference between the adaptive step and the smart adaptive step approaches.
The smart adaptive step approach evaluates a target’s visibility at fewer instances in time, but for each instance in time it requires slightly more work to determine whether a target is visible

Determining Visibility – Ephemeris Uncertainty

- Sequences generated on a weekly basis
- ISS can drift from predicted location due to drag from Low Earth Orbit
- For a target that needs to be visible during the time [st, et], we require it to also be visible during [st-err, et+err] for some err value

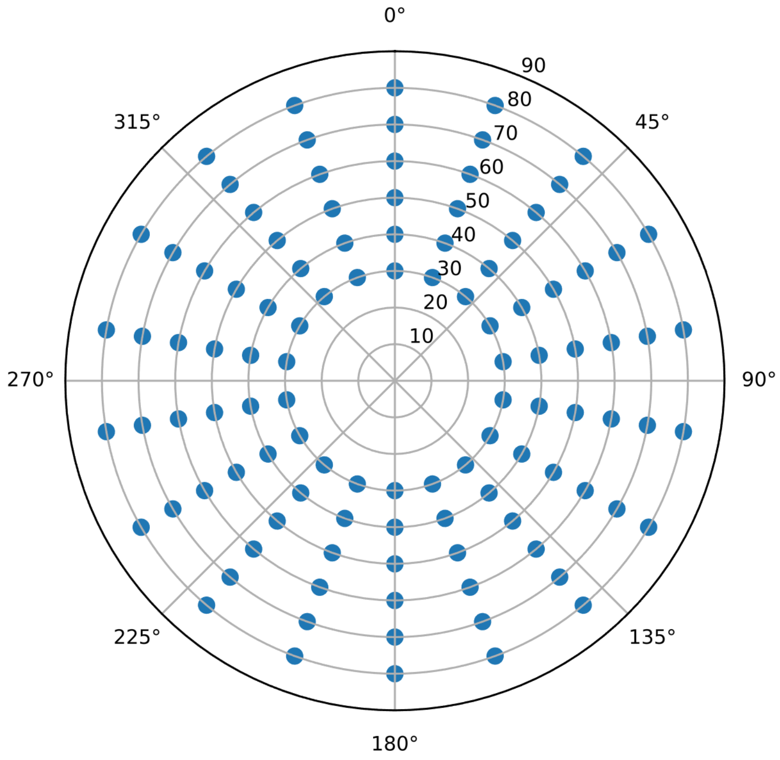
Impact of Checking Visibility – Snapshot Area Map



- Valleys are periods of poor illumination over targets
- Visibility is considerably limited by spacecraft features
- Accounting for 3 seconds of uncertainty in ephemeris does not drastically impact visibility

PMA Calibration

- To calibrate the Pointing Mirror Assembly (PMA), observations are taken from a set of pointings relative to the instrument body
- The observations must be taken over land in daytime to be compared to reference images to determine the error in the pointing based on the ISS location
- Corrections are then applied to minimize the pointing error for future observations.



PMA Calibration – Scheduling

- Initial scheduling goal was to schedule all points with shortest duration schedule
- Create a grid on the Earth's surface
  - Each point is marked as land/water
- Identify land/water boundaries
  - Construct a distance field that gives distance to neatest boundary
  - Accelerates search for valid time windows for when a point is visible over land
- Refine time windows with daylight constraint
- Problem has become Traveling Salesman with Multiple Time Windows

Future Work

- Potentially include ISS attitude predictions to have more accurate visibility checks
- Adaptive Step currently considers nearest point on the Visibility Set boundary, but we could take into account direction of motion to estimate where the point would cross the visibility boundary
  - Could take less conservative step sizes and reduce computation
- Calibration routine benefits from having many images of each point and not just one
  - Schedule more points once minimum requirements are met that still fit in allotted time

Related Work

- Uses of CLASP in other missions:
  - On-orbit scheduling of the IPEX CubeSat (Chien et al. 2015)
  - Long-term mission studies for Europa Clipper, JUICE (Troesch, Chien, and Ferguson 2017), and NISAR (Doubleday and Knight 2014)
  - Scheduling for ECOSTRESS (Yelamanchili et al. 2019)
  - Prototype for early stage mission planning for the THEMIS instrument on Mars Odyssey (Rabideau et al. 2010)

Conclusion

- OCO-3 has four operational modes
    - Nadir
    - Glint
    - Snapshot Area Map
    - Target
- Adaptation to schedule restricted number of Target Mode observations without interfering with Snapshot Area Map
- Multiple approaches to determine visibility of targets
- Scheduling of PMA Calibration Routine

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